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Active erosion–deposition cycles in the hyperarid Atacama Desert of Northern Chile

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ABSTRACT

There is significant debate over the rates and types of fluvial activity at the Plio-Pleistocene boundary in the hyperarid Atacama Desert of Chile. To quantify fluvial processes and help resolve this debate, we measure terrestrial cosmogenic nuclide (TCN) (^{10}Be and ^{21}Ne) concentration depth profiles in three settings representing a chronosequence: (1) a late Pliocene alluvial fan representative of major regional deposits, (2) a modern, active channel and (3) an adjacent low terrace inset into the Pliocene alluvium. Late Pliocene deposits that are widely preserved in the region contain TCN profiles consistent with relatively rapid stripping of upland sediment at the Plio-Pleistocene boundary. Deposits inset into these Late Pliocene features record cut and fill cycles that rework sediment throughout the Quaternary. The TCN profile in the modern channel is best explained by sediment aggradation at 2.1 m Myr^{-1} during the last 250,000 yr. Similarly, the adjacent low terrace sediments contain TCN concentration profiles consistent with aggradation of 2.0 m Myr^{-1} over a period of 250,000–750,000 yr prior to the last 250,000 yr of stability. In summary, depth profiles of two TCNs provide constraints on the rates of sediment deposition, sources of sediment and transport history, as well as the subsequent exposure conditions of the sediment following deposition. Our results are consistent with early Quaternary initiation of hyperaridity for the region. During the Quaternary, winter precipitation events experienced at our sites' latitude (24°S) drive active erosion–deposition cycles. The northward migration of the subtropical front during Quaternary glacial cycles may have enhanced precipitation at 24°S, leading to more active fluvial processes during cooler periods.

1. Introduction

Alluvial landforms of the Atacama Desert of Chile are widely dominated by pre-Pleistocene deposits, and the hyperarid region is remarkable for the modest to negligible Quaternary modification of the landscape (e.g., Dunai et al., 2005). Landscape reconstructions indicate that prominent Miocene and Pliocene alluvial deposits represent large regional erosion/depositional events, whereas Quaternary processes have locally incised into or lap over these regional fluvial deposits (Amundson et al., 2012). Additionally, bedrock hillslopes are covered with dust and salt, and are in large part isolated from present drainage networks. As a result, Quaternary channels are typically left to rework sediment eroded from adjacent Pliocene and Miocene deposits rather than sediment produced from bedrock or saprolite in an actively eroding upland. Constraints on the magnitudes, frequencies and rates of fluvial processes are sparse.

The proposed change in magnitude and nature of the post-Pliocene, Quaternary sedimentary processes in the Atacama Desert should be recorded in terrestrial cosmogenic nuclide (TCN) surface concentrations, as well as in the TCN depth profiles observed in fluvial deposits. Prior work in the Atacama Desert focused on the exposure ages of surface clasts (Dunai et al., 2005; Nishiizumi et al. 2005; Ewing et al., 2006; Gonzalez et al., 2006; Carrizo et al., 2008; Evenstar et al., 2009; Placzek et al., 2010). We show, however, that depth profiles of TCNs, particularly ^{10}Be and ^{21}Ne, provide additional and novel insights into the transport and deposition history of sampled sediment.

To further quantify rates of fluvial processes in the Atacama Desert, we present a dataset of in-situ produced cosmogenic ^{10}Be and ^{21}Ne concentration depth profiles in alluvial sediments from

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the central Atacama Desert that include the regional late Pliocene deposits and younger, localized Quaternary fluvial features inset into this regional landform. To interpret these data, we (1) compare surface concentrations of cosmogenic nuclides to depth profiles, (2) investigate the complexity of sediment exposure histories, and (3) use cosmogenic nuclides to quantify Quaternary deposition in active channels.

1.1. Setting

The Atacama Desert spans approximately 8–10° of latitude within the structurally defined Central Depression of Northern Chile. Three factors are commonly cited as the cause for the region's extreme lack of precipitation: (1) the rain shadow of the Andes to the east, blocking moisture from the Atlantic Ocean; (2) the region's position within the subtropical high-pressure belt; and (3) the upwelling of cold water to the west related to the Pacific Ocean's Humboldt current (e.g., Houston, 2006). Additionally, the Coastal Cordillera between the Central Depression and the Pacific Ocean minimizes the amount of moisture that can reach the Atacama. A north–south gradient in mean annual precipitation sets the boundaries of ecosystems. The hyperarid north (19–23°S) is largely abiotic, and increasing fog and precipitation from 26° to 29°S enables vegetation to begin taking hold near the southern extent of the desert (Navarro-Gonzalez et al., 2003; Rundel et al., 1991; Owen et al., 2011).

Our study is focused within the hyperarid central Atacama Desert, between 21°and 24°S (Fig. 1), an area that now experiences minimal winter rainfall ($<3\ \mathrm{mm\ yr^{-1}}$) sourced from the Pacific Ocean. Specifically, we centered our study around the 24°S latitude, near a boundary between moisture effects from two wind belts, the southern westerlies and the tropical easterlies (Maldonado et al., 2005). North of 24°S, most of the moisture carried by the tropical easterlies is excluded from the northern Atacama Desert by the rain shadow of the Andes. During the summer, however, convective precipitation related to the South American Summer Monsoon can deliver moisture to the eastern edge of the northern Atacama Desert (Zhou and Lau, 1998; Ammann et al., 2001; Placzek et al., 2010). South of 24°S, precipitation thus increases with latitude and is delivered primarily in the form of winter precipitation from Pacific fronts and cutoff lows (Vuille and Ammann, 1997; Latorre et al., 2006; Placzek et al., 2010). The rare precipitation events that have delivered the minimal rainfall recorded near 24°S are most likely attributed to the interception of these cold air masses by increasingly high topography to the east of the Central Depression (Vuille and Ammann, 1997; Placzek et al., 2010). Any past shift in the boundary between these two moisture regimes would be significant to processes active across our study sites since they are near the modern boundary. Independent studies of the late Quaternary paleoclimate of northern Chile suggest that the northernmost boundary of Pacific-derived moisture has shifted toward the equator during recent glacial periods (Lamy et al., 1998; Lamy et al., 2000; Stuut and Lamy, 2004; Maldonado et al., 2005; Heusser et al., 2006). It is therefore possible that the magnitude of precipitation fluctuated to levels higher than that present for hyperarid sites located from 22°S to 24°S, including our study area.

The pace of hillslope and fluvial processes in the Atacama Desert is widely thought to be slower than most places on Earth. However, a growing regional catalog of erosion rates and exposure ages derived from TCN concentrations in bedrock, boulders, and sediment reveals active processes, likely of varying magnitude and duration, from the Miocene to the present (Dunai et al., 2005; Nishiizumi et al., 2005; Kober et al., 2009; Evenstar et al., 2009; Owen et al., 2011; Placzek et al., 2010; Amundson et al., 2012). Such studies also reveal that results from opposite ends of the cosmogenic nuclide-derived surface process rate spectrum mirror the modern day gradient of an increasingly hyperarid climate from 24°S northward. Dunai et al. (2005) reported a wide range of

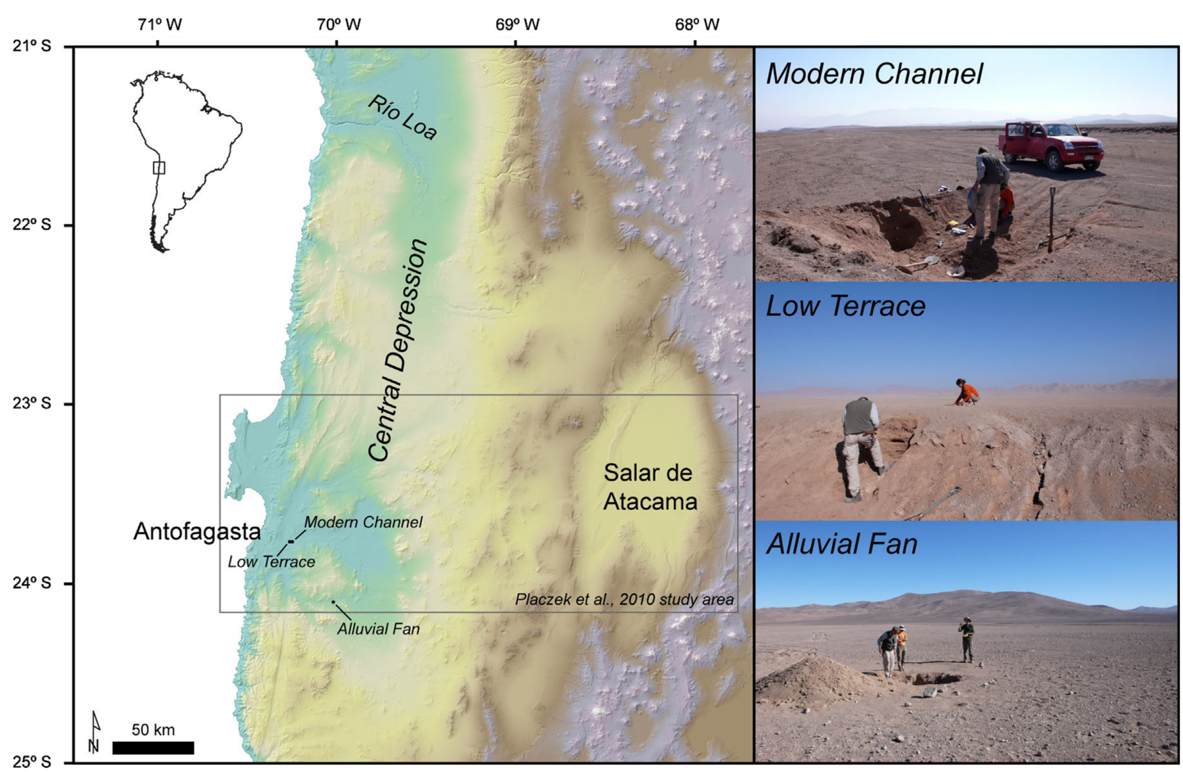

Fig. 1. Sample sites in the hyperarid Atacama Desert of northern Chile. Modern channel and low terrace profiles are east of Antofagasta in the Central Depression. The alluvial fan profile is farther south but within the same geological framework. Inset photographs show field setting for each sample site: modern channel ('Floating Man'), low terrace ('Dancing Bag'), and alluvial fan ('Yungay'). Please see Supplementary Fig. S1 and the Supplementary KMZ file to view higher resolution imagery of each site.